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PLANETARY PHYSICS VII:
ABSORPTION AND PHOTOIONIZATION CROSS SECTIONS OF ATMOSPHERIC GASES AT INTENSE SOLAR EMISSION LINES: N_2, O_2, CO_2, CO, A, AND He

J. A .R. SAMSON   R. B. CAIRNS   F. L. KELLEY

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J. A. R. Samson
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SUMMARY

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Photoionization and total absorption cross sections have been
measured for O_2, N_2, CO_2, CO, A and He at wavelengths in the range
1040Å to 300Å which correspond to intense solar emission lines. These
lines were produced in the laboratory using a high voltage condensed
spark discharge and a dc glow discharge. Many of the lines were com-
pletely resolved by the vacuum monochromator. The wavelength bandpass
was not, therefore, limited to that of the monochromator but to the
widths of the lines generated within the light sources. The widths of
these lines ranged from 0.04Å to 0.1Å.

A short discussion is given of the experimental techniques employed
and of the data obtained.

The work described in this report has been submitted for publication
to the Journal of Geophysical Research.

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LIST OF ILLUSTRATIONS

INTRODUCTION

To determine the energy balance, photochemistry and degree of ionization of the upper atmosphere of the earth and other planets it is necessary to know the neutral gas composition, the concentration of each component gas as a function of altitude and the total energy and spectral distribution of the solar radiation impinging upon these atmospheres.

In recent years knowledge of the solar extreme ultraviolet[*]radiation has increased considerably due mainly to the work of Tousey [1], Hinteregger [2], Friedman [3], Rense [4] and Violett and Rense [5]. The solar spectrum between 2000 Å and the soft X-ray region is now known to be composed mainly of discrete emission lines. The interaction of each of these lines, of frequency ν, with each of the atmospheric gases can be described in terms of a total photoabsorption cross section σ_ν and a photoionization yield γ_ν. Measurements of the cross sections σ_ν are based on Lambert-Beer's Law;

$$I_\nu = I_{o\nu} \exp [-n\sigma_\nu L]$$

where $I_{o\nu}$ is the photon flux, of frequency ν, incident upon the absorbing gas; I_ν is the photon flux transmitted through the absorbing gas; L is the length of the absorption path (in cm) and n is the number density of absorbing particles per cubic centimeter. The absorption cross section can be related to the absorption coefficient k_ν by the expression $\sigma_\nu = k_\nu/n_o$ where n_o is Loschmidt's number. The photoionization cross section $\sigma_{i\nu}$ is given by the product $\gamma\sigma_\nu$ where γ_ν, the photoionization yield is defined as the number of ions formed per photon absorbed by the gas.

If the absorption coefficient varies over the frequency range of the incident radiation, the Lambert-Beer Law will not hold and the apparent absorption coefficient will vary with the number of molecules per cm^2 - column in the absorption cell.

Measured total absorption cross sections can be used to determine the composition and the density profile of atmospheric gases as a function of altitude. The photoionization cross sections enable a free electron production rate to be calculated.

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[*]Numbers in [ ] throughout text indicate reference numbers.

The major constituents of the atmospheres of the Earth, Mars, Venus and Jupiter are listed below:

Earth	N_2	O_2	
Mars	N_2	CO_2	A
Venus	N_2	CO_2	
Jupiter		He	H_2

Minor constituents can be important. For example, atomic oxygen is the dominant specie in the Earth's atmosphere at altitudes between 200 km and 1000 km. Carbon monoxide, a product of the photodissociation of CO_2, is thought to be more abundant than CO_2 in the atmospheres of Mars and Venus above the height of 150 km, Marmo and Schultz [private communication 1964].

In the work described in this report the total absorption and photo-ionization cross sections have been measured of O_2, N_2, CO_2, CO, A and He at wavelengths below 1040 Å which correspond to intense solar emission lines.

During the past ten years photoionization cross sections in O_2, N_2, CO, CO_2, and the rare gases, in the region between 200 and 2000 Å have been reported by various authors. A compilation of these results has been prepared by Schultz, Holland and Marmo [5]. More recently, data have been reported for O_2 and N_2 by Huffman [6 and 7] and by Cook [8].

Very little data exist on the photoionization yields of O_2 and N_2. The early work of Weissler and Associates [9] gives photoionization yields measured with an optimum resolution of 5Å. The only other measurements are those of Watanabe and Marmo [10]. Their measurements, however, were confined to wavelengths longer than 850Å.

Previous measurements of photoabsorption cross sections of CO_2 have been reported by Sun and Weissler [11] and Watanabe (private communication 1963). Watanabe did not extend this work to wavelengths shorter than 850Å. Sun and Weissler, using a line emission source did not obtain data at certain wavelengths important in the solar spectrum eg. 304Å, 584Å and 1025Å. Photoionization yields have been measured by Wainfan, et al.[12] but again with a best resolution of 5Å.

Measurements of the photoabsorption cross sections of CO have been made by Sun and Weissler [11] and Huffman et al.[13]. Photoionization yields have not been measured.

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The two recent cross section measurements in the photoionization continuum of argon, Samson [14] and Rustgi [15] are in good agreement as are experimental and theoretical evaluations of the absorption cross sections in the He continuum, Samson [16] and Stewart and Webb [17]. The photoionization yield in the rare gases is 100%.

For the molecular gases the considerable spread in all the reported data is due, in part, to differences in the wavelength resolution used by the various groups. Molecular nitrogen and carbon monoxide, in particular, exhibit band structure sufficiently narrow that the absorption cross section can change appreciably within a small fraction of an angstrom. Thus, high resolution and precise wavelength identification is required in the absorption measurements. Using a continuum light source the highest resolution obtained photoelectrically, consistent with a useable signal is about $\frac{1}{2}$ Å, and there is a probable uncertainty in the wavelength identification of 0.1Å. To obtain data applicable to the upper atmosphere of the earth and other planets it is, therefore, more appropriate to reproduce the discrete solar lines in the laboratory. This is, of course, difficult to do for lines such as those originating from Mg X. However most of the energy radiated from the sun below 2000Å originates from H, He, O, N and C. All of the lines emitted by these atoms can be generated by laboratory light sources. There are two major advantages in adopting this technique; the first is that the wavelength identification of the lines is known precisely and, secondly, the lines are generally isolated from neighboring lines by several angstroms. Thus a monochromator with moderate resolution can provide a monochromatic line whose width is that generated within the light source. This width is then the actual resolution for the cross section measurement.

Ideally, for application to the planetary atmospheres the lines produced in the laboratory should have the same widths as corresponding lines in the solar spectrum. This point is well illustrated by the asymmetric absorption of the hydrogen Ly γ line by N_2, Ogawa and Cairns [18]. Except for the Ly β line (Tousey [19]) the widths of the solar lines below 1040Å are unknown. The data given below have been obtained with line widths characteristic of the light sources used. In general these lines are less than 0.1Å wide.

EXPERIMENTAL TECHNIQUES

The experimental arrangement is shown in Figure 1 and consisted of a light source, vacuum monochromator, absorption cell and detector. The design of each of these components affects the accuracy of the cross section measurement. Significant errors arise due to the following causes; a drift in light source intensity between measurements of I_o and I; use of a monochromator with insufficient resolution; lack of a suitably precise wavelength calibration; error in determining the gas pressure in the absorption cell and in taking proper account of a pressure gradient and end effects in the cell (a flow system has to be used in this wavelength region); the sensitivity of the detector to stray light and the accuracy of the recording equipment.

Errors have been minimized in the following manner. A drift in the light source intensity causes no error if both I_o and I are measured simultaneously. This is possible at wavelengths shorter than the first ionization potential of the absorbing gas if a double ion chamber is used to serve as both absorption cell and detector in the manner described by Samson [20]. At wavelengths longer than the first ionization potential of the gas it was necessary to use as detector a photomultiplier made sensitive to extreme ultraviolet radiation by a sodium salicylate coating on its end window. High wavelength resolution was obtained using a light source which produced a line spectrum. As previously mentioned the actual resolution for a cross section measurement was then determined by the width of the line, i.e. less than 0.1Å, and was not limited to the resolution of the monochromator which was 0.7Å. The use of a line source allowed an exact wavelength calibration. The magnitude of the pressure gradient in the gas flowing through the absorption cell was reduced by having a small flow rate and using cylindrical cells of large diameter, 8.2 cm. The calculated pressure difference between the ends of the cell under normal operating conditions was less than 1% of the mean pressure. The pressure was measured using a precision McLeod gauge. The error in the number of absorbing particles per cm^2 - coluum which arises in a flow system due to end effects was examined in two ways. Firstly the absorption cross section of O_2 in the Schumann-Runge continuum was measured. At 1436Å the value of 14.8 Mb was obtained. This is in agreement with the extensive measurements of this cross section made by Watanabe and Marmo [10] and Metzger and Cook [21], using static gas absorption cells. These authors claimed an accuracy of $\pm5\%$. Secondly, the cross section for O_2 at 584Å was measured using both the photomultiplier and double ion chamber techniques. These techniques respond differently to end effects. Two absorption cells of lengths 28.6 and 49 cm were used. The results were within 3% of each other.

Errors caused by stray light eg. light scattered within the monochromator or fluorescent radiation from the absorbing gas, were reduced when the double ion chamber was used since light with wavelength longer than the first ionization potential of the gas was not detected.
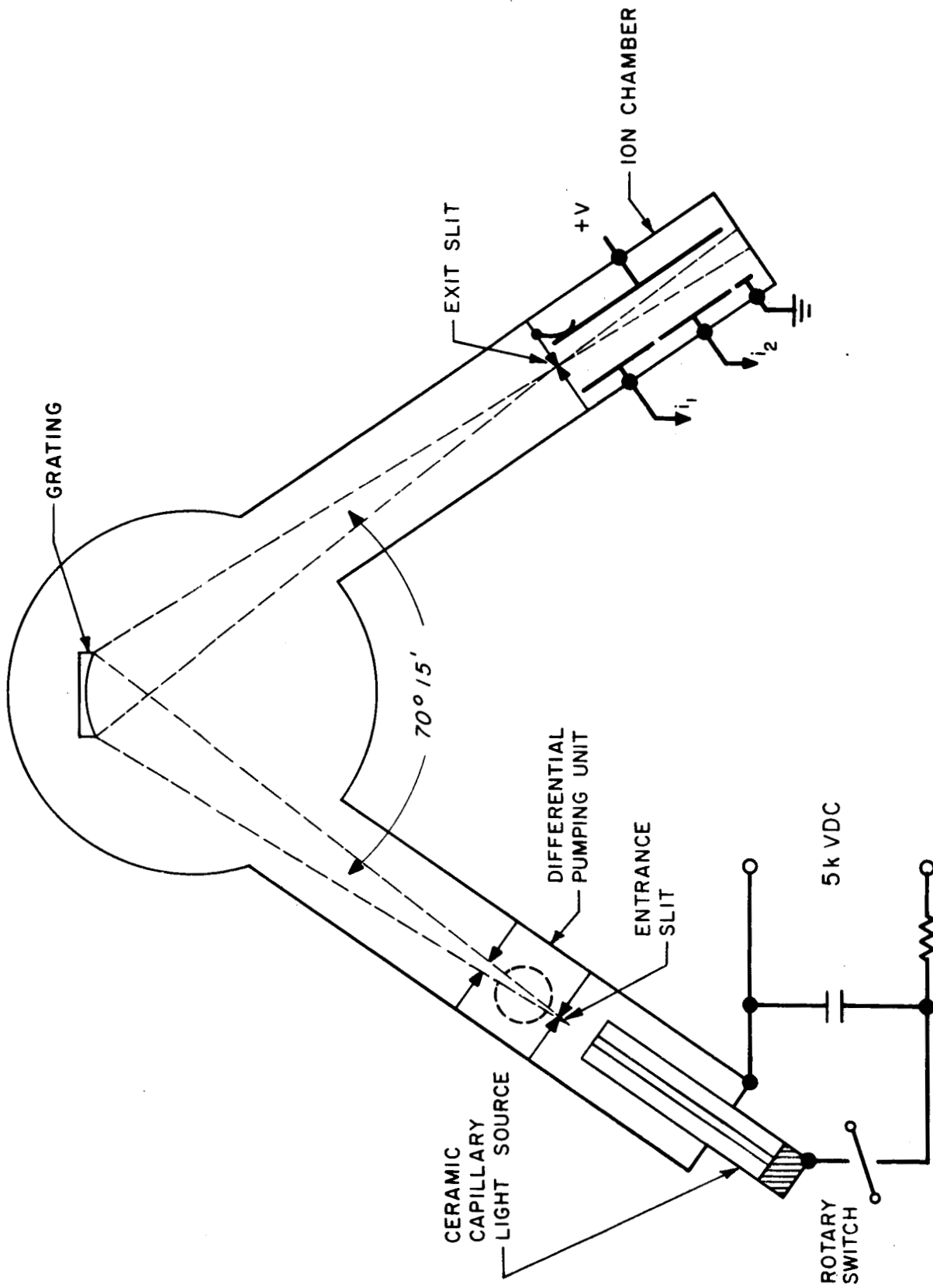
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Figure 1. Experimental arrangement of light source, vacuum monochromator, and absorption cell.

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The ion current and photomultiplier output were measured on micro micro-ammeters calibrated to $\pm 1\%$. For best accuracy the pressure in the absorption cell was adjusted such that the ratio I_o/I was greater than 3 for all measurements.

To measure the photoionization yields the number of ions produced in O_2, N_2, CO_2 or CO, was compared with the number of ions produced in the rare gases by radiation of the same wavelength and intensity. Since the photoionization yield of the rare gases is 100% the yields in O_2, N_2, CO_2 and CO, can be determined. This technique has been described in detail by Samson [20]. To measure the yield of O_2 at wavelengths longer than the ionization potential of xenon (1020Å) a sodium salicylate coated photomultiplier was calibrated, at a wavelength close to 1020Å, against a xenon filled ion chamber and then used to determine the absolute intensity of the incident flux beyond 1020Å. Sodium salicylate has a constant quantum yield in this region if the coating is new (Samson [20]; Knapp and Smith [22]).

Two light sources were used to reproduce the solar radiation. A dc glow capillary discharge produced radiation from excited neutral atoms. To produce the He I lines pure helium was allowed to flow through the light source. In the case of hydrogen the molecular band emission was so profuse that it was impossible to produce the atomic lines isolated from neighboring lines. However, by adding 20% or less hydrogen to a discharge in helium the intensity of the Lyman series can be greatly enhanced and the molecular lines suppressed(Samson [23]). To produce radiation from ionized atoms a high voltage low pressure spark discharge was used. The emission spectrum was characteristic of the gas used in the cases of O_2 and N_2. However, to reproduce the strong solar C III line at 977Å a small amount of CO_2 was added to nitrogen.

Figure 2 illustrates a typical group of lines obtained using the spark light source. The monochromator was able to resolve lines 0.7Å apart in the first order and 0.35Å apart in the second order. Thus, as is shown in Figure 2 some lines were completely isolated while others actually consisted to two lines separated by about 0.1Å. The group of lines at 835Å and similar groups were used in their second order.

A2M normal incidence spectrograph with a plate factor of 3.74Å/mm and a 15μ wide slit was used in its first and higher orders to measure the true line widths originating in the light sources.
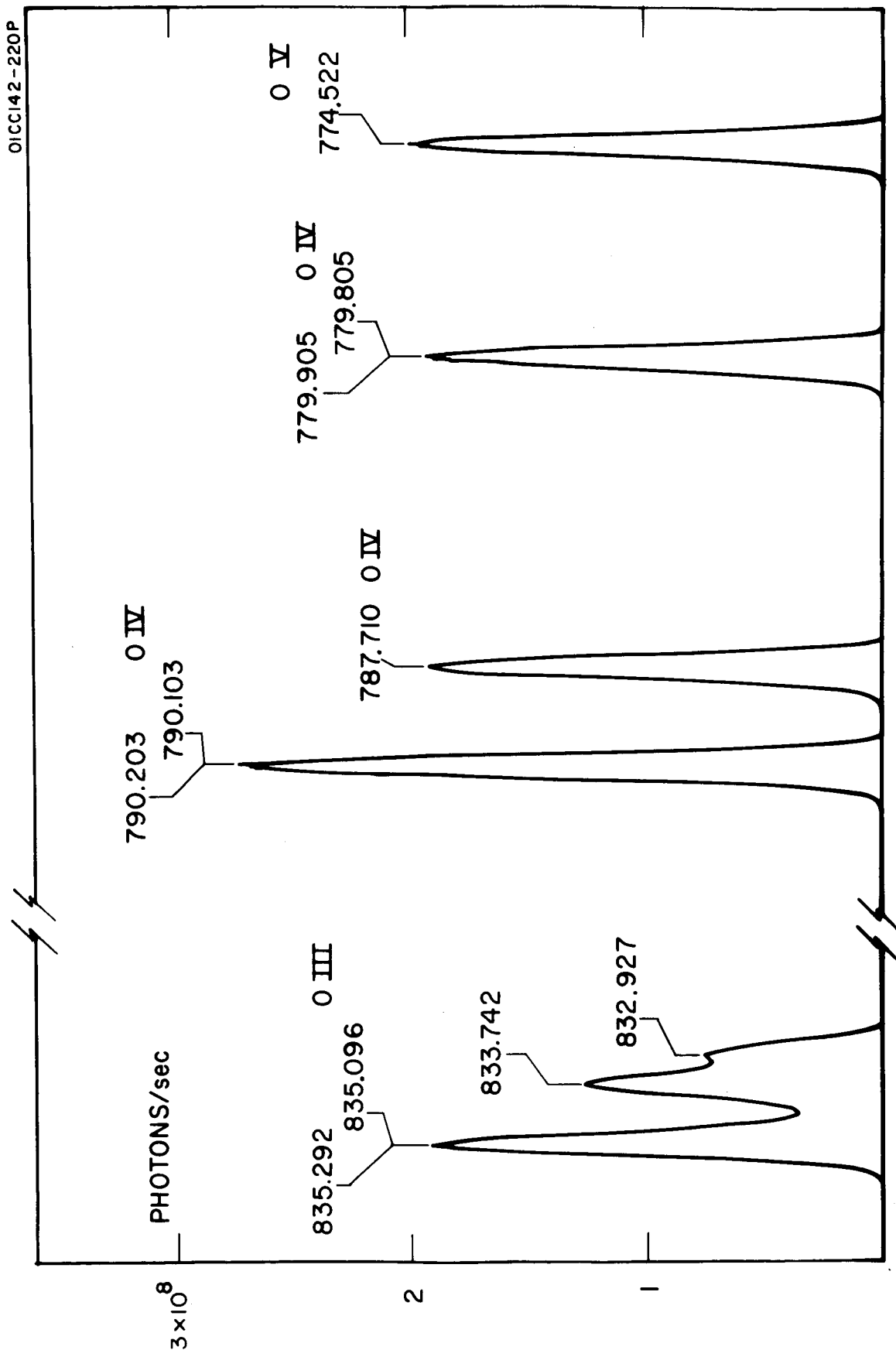
OICCI42-220P

Figure 2. Photoelectric scan of some typical first order lines produced by the spark light source. Measurements using the 830Å group were made in the second order.

RESULTS AND DISCUSSION

Spectral Line Widths

The spectral lines generated by the condensed spark discharge are all broadened or split into two components. This splitting cannot be simply ascribed to an instrumental effect or to Zeeman splitting but is possibly due to the Stark effect. Figure 3 shows the splitting of the lines within the 685Å group of N III as observed in the third order spectrum. The widths of all the lines at their half heights range from 0.04Å to 0.1Å.

The resonance lines of helium and hydrogen were produced by a dc glow discharge. The degree of self reversal and widths of these lines could partially be controlled by varying the pressure within the light source. Figure 4 illustrates the self reversed 584Å line as observed in the fifth order. A densitometer trace of the line is shown below the photograph. The half width of the line in Figure 4 is 0.14Å. The helium pressure in the light source was 0.2 Torr. By decreasing the pressure to 0.06 Torr the half width of the line was reduced to 0.05Å. The absorption data were taken with the 0.14Å wide line except in He, for which this is the resonance line, where two widths were used.

The half widths of the Lyman β and γ lines are 0.08Å and 0.04Å, respectively. Both lines show some self reversal.
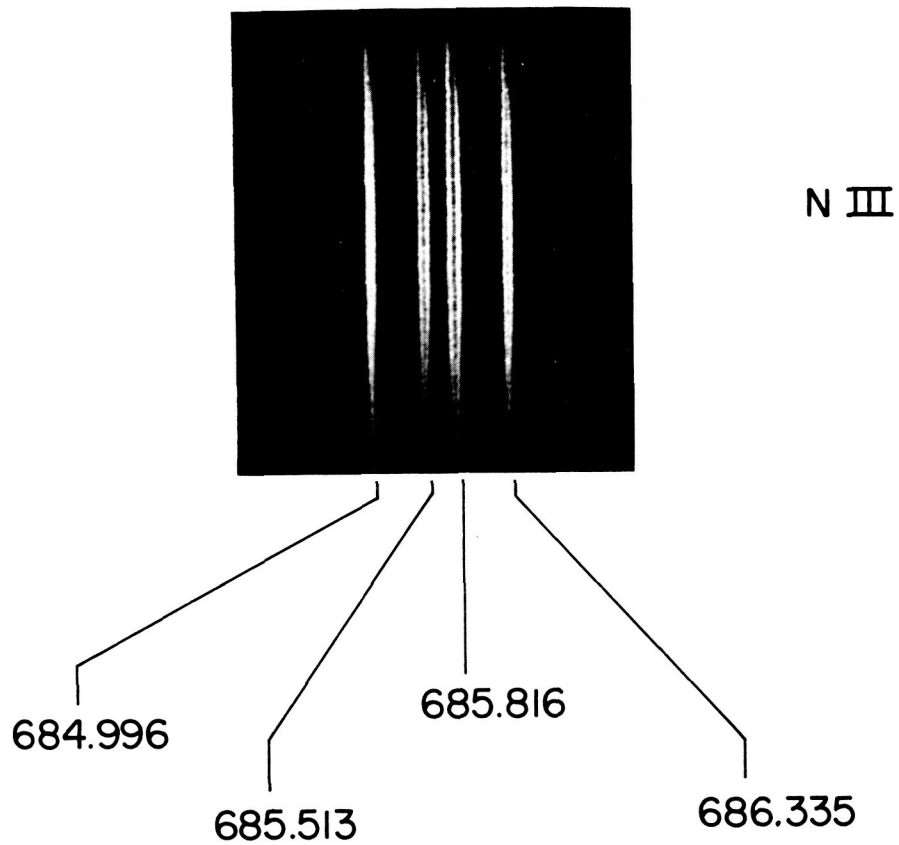
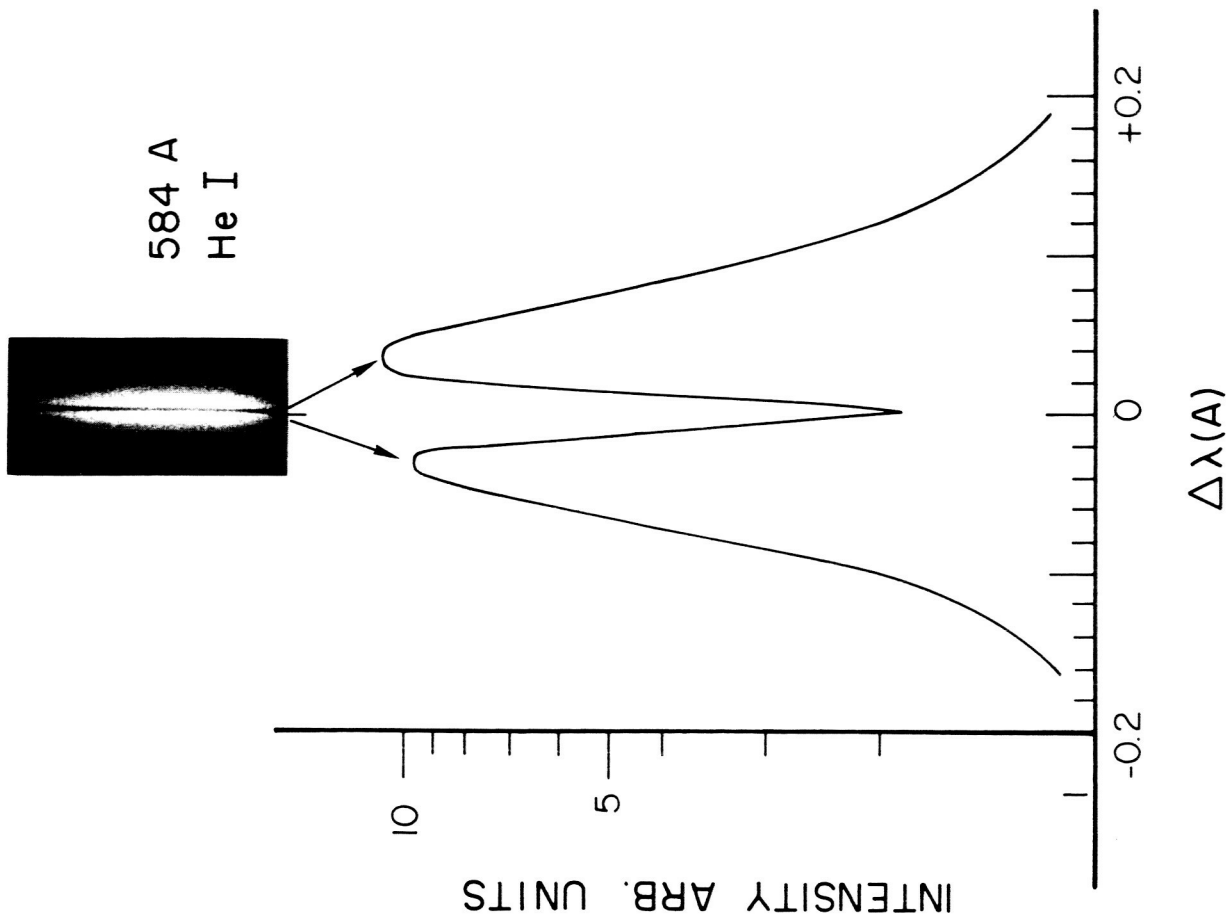Figure 3. Third order spectrum of the 685Å group of N III illustrating the splitting of the lines.

Figure 4. Fifth order spectrum of the 584Å He I line. The half-width is approximately 0.14Å.

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ABSORPTION COEFFICIENTS AND PHOTOIONIZATION YIELDS

Tables 1, 2, 3 and 4, list the absorption coefficients and photo-ionization yields of O_2 and N_2, CO_2 and CO, A, and He respectively. The measurements were made at the most intense solar emission lines lying between 300 and 1040Å. The identification of the solar lines was made from published data obtained from rocket-borne spectrometers (Hinteregger, et al. [2]; (Tousey [19]).

Each of the cross section's listed represents the average of three or more measurements made at different pressures and is believed to be accurate to within $\pm 5\%$ except where otherwise stated. The photoionization yield's represent the first to be measured using the rare gas ion chamber technique. Since this technique is inherently extremely accurate the photoionization yield's are believed to be accurate to within $\pm 5\%$. Most of this error occurs in maintaining the light source intensity constant.

Nitrogen

No absorption coefficients are listed in nitrogen for the 832 - 835Å group nor the 921 - 924Å group. Although most of these lines were clearly resolved by the monochromator it was found that the measured coefficients did not obey Beer's law. As the pressure in the absorption cell increased the apparent absorption coefficients decreased. This pressure effect can by explained by reference to high resolution absorption spectra (Ogawa and Tanaka [24]); (Tanaka and Takamine [25]); (Worley [26]). From such spectra it can be seen that absorption bands in nitrogen coincide with these wave-length groups. The bands in each case are shaded towards longer wavelengths. Although the shading appears continuous it actually represents unresolved discrete rotational lines. The band heads appear at 834.943, 935.163, 920.730, 922.746 and 925.926Å (Worley [26]). Apparently there is some overlapping of the rotational lines with the discrete lines generated by the light source causing the k-value to vary across the width of the incident line thus producing a variation in k with a change in number of molecules per cm^2-column. Many of the rotational lines represent transi-tions from rotational levels in the ground electronic state and since the strength of the absorption transitions from these states depends on their population it will therefore vary with temperature. Thus, the measured absorption coefficients within these bands will depend on the width of the spectral lines, the number of molecules per cm^2-column, and on the temperature.

The 972.5Å Lyman γ line also lies within an absorption band of N_2. The band head lies at 972.07Å (Worley [26]) and is shaded towards longer wavelengths. The absorption coefficient for Lyman γ was found to be 9650 cm^{-1} with a cm^2-column of 1×10^{15} molecules. This large k-value prevented accurate measurements at higher pressures, however, since it

is known that the absorption of Lyman γ varies across its width (Ogawa and Cairns [18]), it is expected that the effective absorption coefficient will decrease with increasing cm^2-column. This would account for Lyman γ being observed at lower altitudes than expected for a $\underline{k}$-value of 9650 cm^{-1}.

Oxygen

In oxygen, as in nitrogen, the absorption coefficient is dependent on pressure at certain wavelengths. A typical example is given by the clearly resolved 833.742 O III line. For an integrated number density of 1×10^{16} molecules per cm^2-column ($\cong$ 200 km) the absorption coefficient is 20.3 cm^{-1} whereas for 2.34×10^{17} molecules per cm^2-column ($\cong$ 122 km) the absorption coefficient is 4.7 cm^{-1}. All the remaining lines in the 830Å and 920Å groups had apparent $\underline{k}$-values less than 10 cm^{-1} when measured at a pressure equivalent to an altitude of 122 km.

An approximate value of 1% for the photoionization yield of O_2 was found at 1032Å although the accepted ionization potential of O_2 is 1026.5Å $\pm$1Å (Watanabe and Marmo [10]). This can be explained by the fact that at room temperature approximately 6% of the oxygen molecules are in sufficiently high rotational levels to be ionized by the 1032Å radiation. Watanabe and Marmo [10] found a yield of 0.7% at 1031Å.

The absorption cross section of N_2 at 1032Å is extremely small, less than 0.00007 Mb. Thus, the 1032Å line will be absorbed in the atmosphere mainly by molecular oxygen whose cross section at that wavelength is 1.04 Mb. To a lesser extent CO_2 will also absorb the 1032Å line since its higher cross section of 14.2 Mb partially compensates for the small amount of CO_2 present in the atmosphere. Rather similar parameters hold for the Lyman β line, namely, 0.001, 1.52 and 15.1 Mb for the N_2, O_2 and CO_2 cross sections, respectively. Since O_2 absorbs more strongly at Lyman β than at the 1032Å line will penetrate lower into the atmosphere than the Lyman β line. Using the appropriate parameters in the 1959 ARDC Model Atmosphere, it can be shown that the 1032Å line is 9 times more intense than Lyman β at 90 km, even although both lines have comparable intensities at the top of the atmosphere (Hinteregger [2]).

Since the 1032Å solar line ionizes O_2 and penetrates to 90 km it must contribute, no matter how slightly, to the ionization of the E-region of the ionosphere. It is of interest, therefore, to compare its contribution to the electron density at 90 km to that of the Lyman β line which has been considered, along with the C III line at 977Å, as possibly controlling the base of the E-region (Watanabe and Hinteregger [2]).

Assume that the absorption cross section at 1032Å for O_2 in rotationally excited states is similar to that for O_2 in its ground state. Then to this approximation the effective photoionization yield at a given temperature is equal to the observed yield at room temperature multiplied by the ratio of molecules in sufficiently high rotational levels to be ionized at room temperature to the number at the given temperature. If this temperature is 160°K, corresponding to an altitude of 90 km, the effective yield is approximately 0.11%.

Using the appropriate constants given above and in Table I it can be shown that the contribution to the electron density at 90 km by the 1032Å line is about 10% that of Lyman β.

The above discussion has assumed an ionization potential of 1026.5Å ±1Å. The energy difference between 1032Å and the ionization potential of the ground state of the O_2 molecule determines the rotational level J above which ionization is possible. The temperature determines the number of molecules in states ≥ J. Within the quoted error limits of the ionization potential the threshold value of J lies between 17 and 20. This means that the number of molecules in sufficiently excited rotational levels to be ionized by the 1032Å line is uncertain by a factor of ~ 3.

The ionization potential of O_2 should be measured more precisely.

Carbon Dioxide

The data presented in this report have been compared with those previously published. Agreement, within the limits of the experimental accuracies claimed, is obtained with the early work of Sun and Weissler [11] at wavelengths shorter than 700Å. In this region the cross sections at all of the wavelengths considered are close to 33 Mb. At longer wavelengths where the cross sections are lower the results are not in accord, those of Sun and Weissler [11] being lower sometimes by as much as a factor of 2. However, at wavelengths longer than 840Å the agreement with Watanabe's recent data, (1963), is good with the exception of the cross section at 972.5Å, Lyman γ.

At this wavelength the apparent cross section depended upon the number of absorbing particles per cm^2-column. The value of 55 Mb, obtained with 2×10^{16} molecules per cm^2-column, is 65% higher than that reported by Watanabe. This difference could arise from the fact that Lyman γ lies within a narrow absorption band. Thus a difference in wavelength resolution could affect the measurement, higher resolution giving a higher apparent cross section. The effective resolution in each of the two experiments could not be compared since it depends upon the half width and degree of self reversal of the Lyman γ line and its intensity relative to neighboring molecular hydrogen lines.

Cross sections were not obtained at the wavelengths 923.045 and 923.211Å since these two lines, which were not separately resolved, lie on the edge of an absorption band and their individual cross sections differ largely.

At certain wavelengths the absorption cross sections for CO_2 are considerably larger than for either O_2 or N_2, e.g., at Lyman β, 1025.72Å. At this wavelength the cross sections are 1.52, 0.001 and 15.1 Mb for O_2, N_2 and CO_2 respectively. In the Earth's atmosphere above 95 km the number of CO_2 molecules per cm^2-column is only about 1% of the number of O_2 molecules per cm^2-column (1959 ARDC Model Atmosphere). However the Lyman β flux is significantly attenuated by CO_2. At 99 km CO_2 will account for a 6% reduction in the intensity of the incident Lyman β flux. At 97 km this reduction is 9% and at 95 km is 14%.

Carbon Monoxide

At the wavelengths where direct comparison is possible the data presented in this paper have values most of which are about 20% greater than those given in the photographic work of Sun and Weissler but approximately 25% less than the recent work, using photoelectric detection but lower resolution, of Huffman et al. [13]. Huffman has reported that at a number of strong bands with wavelengths longer than the first ionization threshold, most of which are not classified, the absorption cross section was a function of the number of particles per cm^2-column. This is due to rapid changes in cross section across the rotational lines of these bands. In the present work, even with a resolution of less than 0.1Å the cross sections were pressure dependent. At each of these wavelengths therefore, three 'apparent' cross sections are listed in the table with the corresponding numbers of particles per cm^2-column.

Argon

For argon between 466 and 424Å the cross section varies considerably due to the presence of a Rydberg series of autoionized lines, Madden and Codling [27], Samson [28]. The only solar line considered in this region, at 434.975Å, lies within the discrete absorption structure due to the third member of this Rydberg series corresponding to the transition $3s^23p^6 - 3s3p^66p$. Its absorption cross section is 19.7 Mb and its yield 100%.

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Helium

In addition to absorption within the ionization continuum resonance line absorption at 584Å is of importance. With no knowledge of the precise shape of the solar 584Å line its apparent cross section cannot be determined. Po Lee and Weissler [29] gave a value of 2.7 Mb but did not specify the width of their source line. Apparent cross sections obtained under different experimental conditions illustrate the variation to be expected. For a self reversed line of half width 0.14Å and 1.3×10^{17} absorbing particles per cm^2-column σ apparent = 4.7 Mb. For a line of half width 0.05Å, also self reversed and 1.6×10^{15} absorbing particles per cm^2-column σ apparent = 225 Mb. These values can be compared with the maximum absorption cross section, $\sim 2 \times 10^5$ Mb, calculated for the Doppler broadened absorption line (temperature $20°C$) using the theoretical f-value 0.275, Dalgarno and Stewart [30].

TABLE 1. Absorption Coefficients, Cross Sections and Photoionization Yields of O_2 and N_2.

Source Line λ(A)	Oxygen			Nitrogen		
	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$
303.781 He II	446*	16.6	100	326*	12.1	100
429.918 O II 430.041 O II 430.177 O II	480*	17.8	100	564*	21.0	100
434.975 O III	561	20.9	100	637	23.7	100
498.431 O VI	619	23.0	100	652	24.2	100
507.391 O III 507.683 O III	622	23.1	97	654	24.3	100
508.182 O III	638	23.7	97	598	22.2	100
519.610 O VI	678	25.2	100	693	25.8	98
522.208 He I	561	20.9	99	635	23.6	97
525.795 O III	659	24.5	97	703	26.2	98
537.024 He I	571	21.2	98	678	25.2	97
553.328 O IV	705	26.2	93	669	24.9	96
554.074 O IV	685	25.2	97	680	25.3	93
554.514 O IV	709	26.4	97	660	24.6	93

*Estimated error ±10%

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TABLE 1. (Continued)

Source Line λ(A)	Oxygen			Nitrogen		
	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$
555.262 O IV	698	26.0	97	666	24.8	95
584.331 He I	625	23.2	98	620	23.1	100
597.818 O III	774	28.8	92	629	23.4	97
599.598 O III	765	28.4	97	629	23.4	95
608.395 O IV	648	24.1	94	630	23.4	100
609.705 O III 609.829 O IV 610.043 O III	714	26.6	94	636	23.7	100
610.746 O III 610.850 O III	764	28.4	96	626	23.3	99
616.933 O IV 617.033 O IV 617.051 O II	655	24.4	97	637	23.7	98
624.617 O IV	681	25.3	93	645	24.0	97
625.130 O IV	661	24.6	96	642	23.9	97
625.852 O IV	814	30.3	96	644	24.0	98
629.732 O V	801	30.0	97	652	24.2	97
684.996 N III	709	26.4	100	653	24.3	95

TABLE 1. (Continued)

Source Line	Oxygen			Nitrogen		
$\lambda(A)$	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$
685.513 N III 685.816 N III	496	18.4	100	670	24.9	95
686.335 N III	594	22.1	100	648	24.1	95
758.677 0 V	493	18.3	57	643	23.9	75
759.440 0 V	463	17.2	53	313	11.6	86
760.229 0 V 760.445 0 V	498	18.5	49	531	19.8	57
761.130 0 V	547	20.3	51	1077	40.1	55
762.001 0 V	545	20.3	50	747	27.8	46
763.340 N III	604	22.5	58	734	27.3	80
764.357 N III	479	17.8	60	364*	13.5	69
765.140 N IV	615	22.9	54	2295	85.4	77
774.522 0 V	382	14.2	63	914	34.0	40
779.821 0 IV 779.905 0 IV	733	27.3	33	344	12.8	65
787.710 0 IV	644	24.0	54	226	8.41	89
790.103 0 IV 790.203 0 IV	744	27.7	37	610	22.7	45
832.754 0 II 832.927 0 III	707*	26.3	38	Variable See Text		0

*Estimated error ±10%

TABLE 1. (Continued)

Source Line λ(A)	Oxygen k(cm^{-1})	σ(Mb)	γ(%)	Nitrogen k(cm^{-1})	σ(Mb)	γ(%)
833.326 O II	-	-	-			
833.742 O III	350*	13.0	39	Variable See Text		0
834.462 O II	285*	10.6	38			0
835.096 O III / 835.292 O III	267	9.93	37			0
921.982 N IV	148	5.50	79			0
922.507 N IV	171	6.36	84			0
923.045 N IV / 923.211 N IV	272	10.1	88			0
923.669 N IV	246	9.15	90			0
924.274 N IV	480	17.8	83			0
972.537 H I	860	32.0	83			0
977.026 C III	107	3.98	62	2.2	0.082	0
989.790 N III	37	1.38	69	4.5	0.167	0
991.514 N III / 991.579 N III	47	1.75	69	2.0	0.074	0
1025.722 H I	41	1.52	64	0.027	0.0010	0
1031.912 O VI	28	1.04	1**	<0.02	0.00074	0
1037.613 O VI	21	0.78	0.1**	<0.02	0.00074	0

**Estimated error ±50%

*Estimated error ±10%

TABLE 2. Absorption Coefficients, Cross Sections
and Photoionization Yields of CO_2 and CO.

Source Line λ(A)	Carbon Dioxide			Carbon Monoxide		
	k(cm^{-1})	σ(Mb)	γ(%)	k(cm^{-1})	σ(Mb)	γ(%)
303.781 He II	630*	23.4*	100	307*	11.4*	93*
434.975 O III	743	27.6	100	519	19.3	100
507.391 O III ⎫ 507.683 O III ⎬	807	30.0	100	574	21.4	100
508.182 O III	778	28.9	100	568	21.1	98
522.208 He I	802	29.8	98	576	21.4	100
525.795 O III	838	31.2	100	580	21.6	97
537.024 He I	845	31.4	96	610	22.7	98
553.328 O IV	909	33.8	100	599	22.3	97
554.074 O IV	818	30.4	100	595	22.1	97
554.514 O IV	894	33.2	100	590	21.9	97
555.262 O IV	911	33.9	100	608	22.6	98
584.331 He I	919	34.2	99	609	22.6	97
597.818 O III	953	35.4	100	615	22.9	97
599.598 O III	952	35.4	100	616	22.9	97
608.395 O IV	951	35.4	100	611	22.7	98
609.705 O III ⎫ 609.829 O IV ⎬ 610.043 O III ⎭	949	35.3	100	601	22.4	98

*Estimated error ±10%

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TABLE 2. (Continued)

Source Line λ(A)	Carbon Dioxide			Carbon Monoxide		
	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$
610.746 0 III } 610.850 0 III	953	35.4	100	593	22.1	98
616.933 0 IV 617.033 0 IV 617.051 0 II	947	35.2	100	607	22.6	97
624.617 0 IV	918	34.1	100	610	22.7	98
625.130 0 IV	927	34.5	100	607	22.6	98
625.852 0 IV	954	35.5	100	593	22.1	98
629.732 0 V	922	34.3	100	593	22.1	98
684.996 N III	968*	36.0*	96	596	22.2	100
685.513 N III } 685.816 N III	918	34.1	97	595	22.1	100
686.335 N III	948*	35.2*	93	590	21.9	100
758.677 0 V	1009	37.5	86	616	22.9	57
759.440 0 V	839	31.2	89	724	26.9	65
760.229 0 V 760.445 0 V	1185	44.1	89	457	17.0	64
761.130 0 V	1206	44.8	86	374	13.9	75
762.001 0 V	1147	42.6	92	353	13.1	78
763.340 N III	1238*	46.0*	90	628	23.4	68

*Estimated error ±10%

TABLE 2. (Continued)

Source Line λ(A)	Carbon Dioxide			Carbon Monoxide		
	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$	$k(cm^{-1})$	$\sigma(Mb)$	$\gamma(\%)$
764.357 N III	1635*	60.8	91	1011	37.6	46
765.140 N IV	2527	93.9	92	626	23.3	57
774.522 O V	996	37.0	77	678	25.2	56
779.821 O IV ⎫ 779.905 O IV ⎭	1216	45.2	86	1049	39.0	67
787.710 O IV	857	31.9	84	434	16.1	67
790.103 O IV ⎫ 790.203 O IV ⎭	624	23.2	80	540	20.1	74
832.754 O II ⎫ 832.927 O III ⎭	359**	13.8**	89	514**	19.1**	80
833.742 O III	277**	10.3**	87	486**	18.1**	88
834.462 O II	341	12.7	88	510	19.0	92
835.096 O III ⎫ 835.292 O III ⎭	385	14.3	87	474	17.6	94

At the following wavelengths, which are longer than the ionization threshold of both CO_2 and CO, the measured cross sections of CO were pressure dependent. In these cases three values of the cross section are given together with corresponding numbers (N) of absorbing particles per cm ^{2}-column. The symbol (***) has been used to indicate no pressure dependence.

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*Estimated error ±10%

**Estimated error ±20%

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TABLE 2. (Continued)

Source Line λ(A)	Carbon Dioxide			Carbon Monoxide		
	$k(cm^{-1})$	$\sigma(Mb)$	$N(cm^{-3})$	$k(cm^{-1})$	$\sigma(Mb)$	$N(cm^{-3})x10^{-16}$
				239	8.88	2.60
921.982 N IV	2695	100	***	173	6.43	8.33
				166	6.17	15.6
				1214	45.1	2.60
922.507 N IV	1240	46.1	***	885	32.9	8.33
				733	27.3	15.6
				896	33.3	2.60
923.045 N IV ⎫						
⎬ See Text				815	30.3	8.33
923.211 N IV ⎭				669	24.9	15.6
				426	15.8	2.60
923.669 N IV	1516	56.4	***	389	14.5	8.33
				368	13.7	15.6
				406	15.1	2.60
924.274 N IV	1526	56.7	***	313	11.6	8.33
				253	9.40	15.6
				129	4.80	37.8
972.500 H I	See Text			102	3.79	64.8
				94.8	3.52	119.

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TABLE 2. (Continued)

Source Line λ(A)	Carbon Dioxide			Carbon Monoxide		
	$k(cm^{-1})$	$\sigma(Mb)$	$N(cm^{-3})$	$k(cm^{-1})$	$\sigma(Mb)$	$N(cm^{-3})x10^{-16}$
977.000 C III	1154	42.9	***	10.5	0.39	323.
				9.5	0.35	604.
				7.4	0.28	1630.
989.790 N III	623	23.2	***	163	6.06	15.6
				76	2.83	95.7
				66.4	2.45	150.
991.514 N III	1603	59.6	***	42.6	1.58	15.6
				32.4	1.20	95.7
991.579 N III				32.2	1.20	150.
1025.720 H I	407	15.1	***	<0.4	<0.015	
1031.912 O IV	383	14.2	***	<0.4	<0.015	
1037.613 O VI	367	13.6	***	<0.4	<0.015	

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TABLE 3. Absorption Coefficients and Cross Sections of A.

Source Line λ(A)	$k(cm^{-1})$	$\sigma(Mb)$	Source Line λ(A)	$k(cm^{-1})$	$\sigma(Mb)$
303.781 He II	60*	2.23*	617.033 O IV	982	36.5
434.975 O III	531	19.7	617.051 O II	982	36.5
507.391 O III	938	34.9	624.617 O IV	981	36.5
507.683 O III	938	34.9	625.130 O IV	980	36.4
508.182 O III	940	34.9	625.852 O IV	980	36.4
522.208 He I	953	35.4	629.732 O V	979	36.4
525.795 O III	957	35.6	684.996 N III	943	35.0
537.024 He I	963	35.8	685.513 N III	942	35.0
553.328 O IV	973	36.2	685.816 N III	942	35.0
554.074 O IV	974	36.2	686.335 N III	942	35.0
554.514 O IV	974	36.2	758.677 O V	864	32.1
555.262 O IV	975	36.2	759.440 O V	862	32.0
584.331 He I	983	36.5	760.229 O V	860	32.0
597.818 O III	985	36.6	760.445 O V	860	32.0
599.598 O III	985	36.6	761.130 O V	859	31.9
608.395 O IV	984	36.6	762.001 O V	857	31.9
609.705 O III	984	36.6	763.340 N III	854	31.7
609.829 O IV	984	36.6	764.357 N III	852	31.6
610.043 O III	984	36.6	765.140 N IV	850	31.6
610.746 O III	983	36.5	774.522 O V	836	31.0
610.850 O III	983	36.5	779.821 O IV	676	25.1
616.933 O IV	982	36.5	779.905 O IV	676	25.1

*Estimated error ±10%

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TABLE 4. Absorption Coefficients and Cross Sections of He.

Source Line λ(A)	$k(cm^{-1})$	σ(Mb)
303.781 He II	74*	2.75*
429.918 O II	154	5.73
430.041 O II	154	5.73
430.177 O II	154	5.73
434.975 O III	157	5.84
498.431 O VI	196	7.29
584.331 He I	See Text	

*Estimated error $\pm$10%.

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